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EXPERIMENTAL INVESTIGATIONS ON INJECTION MOLDED PARTS OF MECHANICALLY RECYCLED OFFCUTS FROM THE PRODUCTION OF CONTINUOUS FIBER-REINFORCED THERMOPLASTIC SHEETS

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ABSTRACT

This paper describes investigations of the recycling and re-use of remnants from semi-finished part preparation of continuous-fiber reinforced plastic sheets. The polymer sheets consist of a Polyamide 6 matrix with glass-fiber fabric. The sheets are produced as a fiber-reinforced band in a continuous process, which is then machined in a following process using a water-jet cutting unit. Material remnants are produced during this stage; the possibility examined here is whether these remnants can be entirely recycled and re-used in an injection-molding process. To do so, the material remnants must be shredded to recyclate. Following that, the recyclate is processed on a twin-screw extruder in order to produce fiber-reinforced plastic granule, which should replace standard fiber reinforced plastic granules used in the injection molding process. The primary focus of the investigations described here is a characterization of the mechanical properties which it is possible to achieve after completing both the twin-screw extrusion and the injection molding. Over the course of these experiments, the granule is used to produce test specimens while varying the injection molding parameters. Tensile strengths of 187 MPa, elasticity moduli of 21 GPa, and impact strength of 56 kJ/m^2 are determined in mechanical testing after production.

1. INTRODUCTION

The sustainable use of resources has become a critical topic in the 21st century. The reasons for this include the continually shrinking availability of, for example, crude oil or metals. This has led, and will lead further to re-thinking the handling of scraps and remnants in industrial production. More and more, recycled materials are being used to produce new products.

Another topic that has also gained prominence due to the trend of sparing material use is that of lightweight construction. Lightweight constructions, for example in the automobile industry, contribute to the saving of fuel. Overwhelmingly, fiber-reinforced plastics are the material of choice for lightweight design, due to their exemplary high weight-to-strength ratio, as well as their stiffness. This increasing affinity for lightweight construction, as well as increasing efforts to recycle scrap material, can be taken together as signs of the significance of the topic of recycling lightweight materials.

When producing and processing continuous-fiber reinforce thermoplastics (CFRT), which in the form of large-sheet composites are known as organic sheet, remnants of pure material are produced; currently, only thermal disposal of these scraps is being carried out.

These monofraction-material remnants, in this case glass-fiber-reinforced PA6, are also eminently suitable for material-based recycling and re-use due to the chemical characteristics of the thermoplastic matrix polymer. In contrast to cross-linked polymers, the application of energy allows these polymers to be re-melted. Once melted, the polymer can then be used for producing a new product. The goal is to be able to use recycled material obtained from the remnants of cut CFRT to produce injection-molded products in place of typical fiber-reinforced plastic granules specially produced for the process. The cuttings are first shredded into smaller pieces in order to obtain suitable starting material for the twin-screw extrusion, and thus for the granule production.

2. PRODUCING THE MATERIAL

The high-strength remnants of glass-fiber-reinforced Polyamide 6, with a tensile strength of 404/390 MPa (longitudinal/transversal), require the use of a robust shredder. A single-shaft shredding machine has shown itself to be particularly suitable for this purpose due to its massive, sturdy construction and its high-power drive capability of 22 kW. The use of a segmented screen with a hole diameter of 8/10 mm regulates the particle size of the shredded particles.

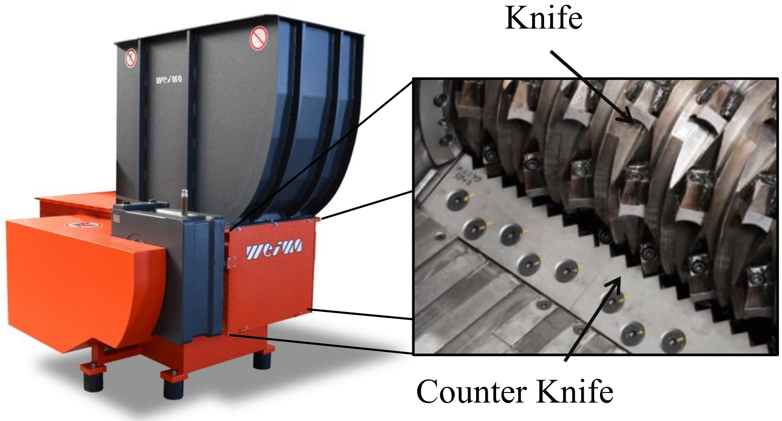


Figure 1: Multipurpose Shredder WLK 4 (Source: WEIMA Maschinenbau GmbH)

The sieving and the subsequent evaluation of the weight proportions can be used to generate a particle size distribution chart. Based on this distribution, the fiber length in the recycled material can be estimated. This estimation is based on the assumption that the particles contain exclusively continuous fibers.

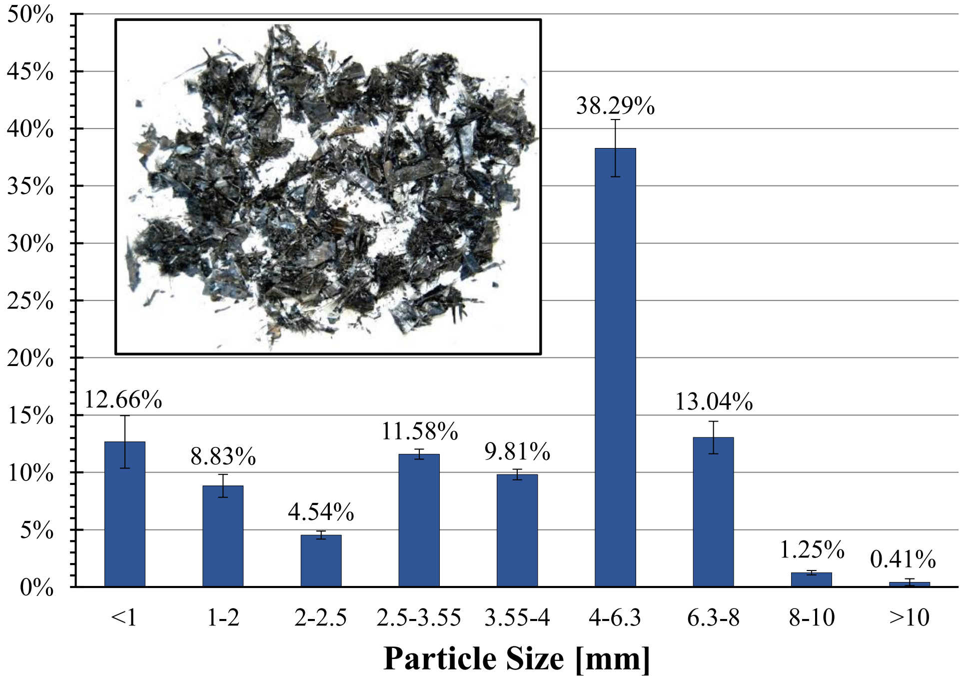


Figure 2: Particle Size Distribution of the shredded Material

It is clear from Figure 2 that more than 98% of the fibers are shorter than 8 mm. The majority of the particles in terms of numbers are between 4 and 6.3 mm. This makes clear that the length of the fibers in the shredded material is still sufficient to produce a strengthening effect, as the fiber lengths are still above the critical fiber length [5].

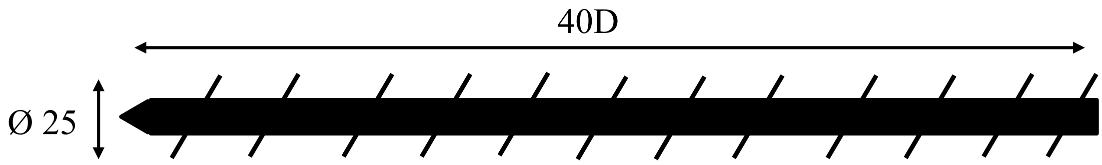
The production of granule from shredded material is done in a twin-screw extrusion process. The small flight depth of the screw in the feed zone limits the size of the particles used to 8 mm. Because of this, the particles must be sieved to ensure only the inclusion of particles which are 8 mm or smaller.

3. EXPERIMENTAL SETUP

In addition to direct processing in an injection molding process, the production of granule from shredded material is another method of enabling the re-use of CFRT sheets intended for recycling. In contrast to direct processing, the granule can be processed on standard injection molding equipment.

3.1 Pelletizing

For the production of granule from recycled material, a ZSK 25-model twin-screw extruder from the company Werner & Pfleiderer is used. In this machine, both screws have a diameter of 25 mm and each screw shaft is capable of transmitting a maximum torque of 84 Nm. The cylinder setup used here has a length of 40D. The screw configuration consists primarily of elements with only minor shearing effects (Figure 3); this minimizes breaking and thus shortening of the fibers during processing.



Quantity of screw elements	1	1	3	1	16	1	2	1	2	3	2
Screw element (pitch/length)	16/16	24/12	24/24	36/18	36/36	24/24	KB45/5/36	24/24	KB45/5/36	48/24	36/36 SK

SK: Thrust Flight Element
KB: Kneading Block

Figure 3: Screw Configuration

Processing of the shredded material takes place at a processing temperature of 270° C and at a speed of 350 rpm. The material is fed in through the main feed hopper at a rate of 11 kg/h. Dosing is done gravimetrically. Due to the poor trickling properties of the shredded material, feeding equipment with a flex-wall hopper is employed. A spiral screw with a pitch of 60 mm and a diameter of 40 mm is used as well. In addition to the highly flexible hopper wall, the free-moving volume in the feed zone provided by the screw geometry also ensures the loosening of any material blockages in the hopper. This leads to a consistent dosage of shredded material, which is necessary to produce homogenous granule (Figure 4) in a submerged granule-production process.

Figure 4: Granule Produced in the Twin-Screw Process

3.2 Specimen Production

According to the DIN EN ISO 294-1 standard, injection molding is a suitable process for the production of testing specimens to determine characteristic mechanical values. With an Allrounder 270 S injection molding unit from the company Arburg, specimens of the type 1B (DIN 527-2) are produced. Before producing the specimens, the granule is dried at 80° C over 5 hours in a hot-air dryer.

As the process introduced here is an entirely new one for the recycling and re-use of CFRT, the mechanical characteristics of products produced with these granule are unknown and thus of particular interest. Apart from the material properties of the granule, the process parameters during injection molding are above all responsible for the mechanical properties of the specimens. In particular during the plasticization of the polymer melt, the fibers are shortened in the processing unit. This is conditioned by the parameters selected, which create differing interactions between fiber/fiber, fiber/wall, and fiber/polymer [1], [3]. For this reason, selected plasticizing parameters are varied in order to examine the effect of the resulting fiber shortening on the mechanical properties of the specimen. These include the back pressure, the temperature, and the dosing speed (Table 1).

Table 1: Varied Injection Parameters

	Factor Level		
	-1	0	+1
Temperature [°C]	280	-	290
Back pressure [bar]	40	60	80
Dosing Speed [1/min]	20	30	40

The influence of the injection molding parameters on the mechanical properties will be exemplified by the properties mechanical impact strength, Young's modulus, and tensile strength.

4. EXPERIMENTAL INVESTIGATIONS

The tensile strength of the specimens produced is determined in a uniaxial tensile test according to DIN EN ISO 527-1, with a testing speed of 5 mm/min. The testing speed to determine the Young's modulus is 1% L_0 / min. As a sample size, 5 specimens are tested. At the time of the test, the specimens were fresh from the mold.

As an additional mechanical characteristic value, the impact strength is determined according to DIN EN ISO 179-1/1eU. To do so, a Hit-model pendulum-impact testing machine from the company Zwick is used. 5 freshly molded specimens are tested. During the test, a 5 J pendulum is used.

The tensile strength and the impact strength are dependent on, among other factors, the proportion of fibers and the fiber length in the plastic granule, as well as on the resulting fiber length in the specimens themselves [5]. The reproducibility of the twin-screw extrusion, i.e. the production of homogeneous granule, in relation to the proportion of fibers is evaluated based on randomly sampled measurements of fiber proportion.

The measurement of the mass percentage of fibers ψ is carried out in an ashing process according to DIN EN ISO 3451-1. The polymer matrix is completely decomposed in a furnace over the course of 60 minutes at a temperature of 600° C. The amount of fibers remaining is determined gravimetrically and compared to the initial specimen mass. The mass percentage of fibers ψ is determined using a sample of 3 specimens.

Further, these remaining fibers are used to determine the length of fibers in the granule. The fiber length is specified via optical measurement. To do so, the fibers are applied to microscope slides and digitalized using an optical scanner. Optical-recognition software is then used to identify and to measure said fibers. For this fiber-length measurement, 6 slides are prepared from each of 3 specimens and measured digitally.

5. RESULTS

For the evaluation of the fiber length measurements after granule production, the average fiber percentage is calculated from the result of 3 measurements. The homogeneity of the granule is to be investigated using granule samples which are randomly taken after 0, 10, 20, 30, 40, 45, 50, and 55 minutes of processing. Inhomogenous areas could have occurred due to the separation of the recycled material during dosing or during the transport phase.

At less than 1%, the small maximum devations in fiber percentage (Figure 5) show that similar fiber percentage can be consistently reproduced. This indicates a homogenous distribution of the fibers in the recycled material. Furthermore, it is evident that the fiber percentage in the recycled material tends to hover around 64%.

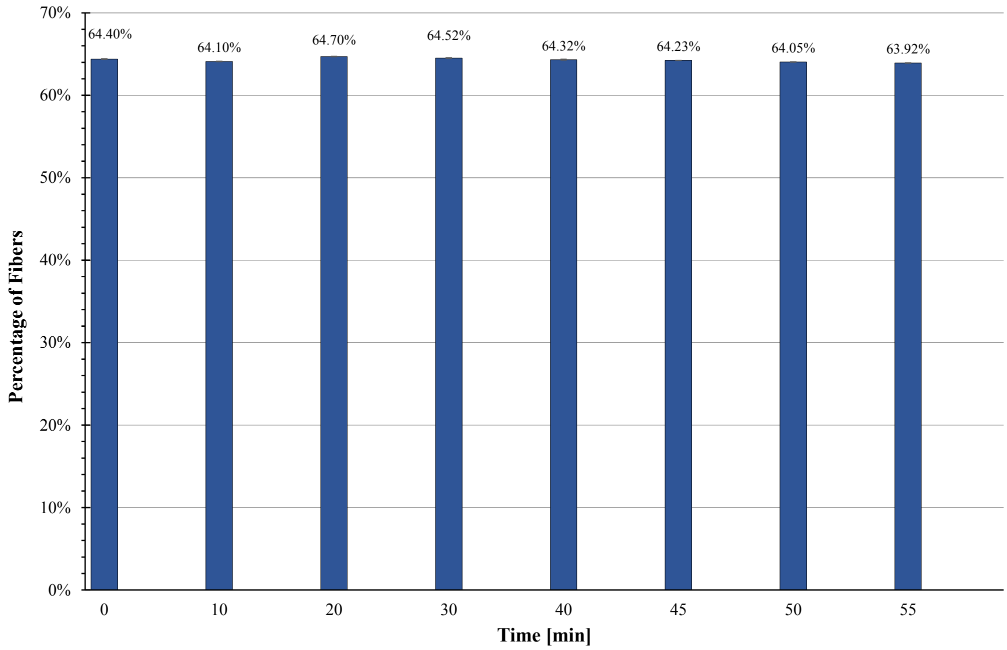


Figure 5: Fiber Content ψ of Continuously Produced Granule

In addition to the fiber percentage, the length of the fibers in the granule has been examined. The shortening of fiber length in comparison to the fiber length in the recycled material can thus be clearly seen here; this is significant, as the fiber length is decisive for the mechanical properties of the specimens. Based on the fiber length, the apparent influence on the strength and the stiffness of the specimens is described generally with a fiber length effectiveness factor [2].

The distribution of fiber lengths shown in Figure 6 represents an average from 18 digitally measured optical measurements. Additionally, the standard deviations are included in the bar chart. The fiber length distribution clearly shows a significant reduction in fiber length during the twin-screw process. While fiber lengths in the recycled material are well above 1 mm (Figure 2), the fibers here have been shortened to less than 1 mm.

The fiber length distribution shown in Figure 6 is typical for short-fiber-reinforced plastic granules [4]. The average fiber length for short-fiber-reinforced polymer granules lies roughly within a range from 200 µm to 1000 µm. For the granule examined here, an average fiber length of 296.8 µm is measured.

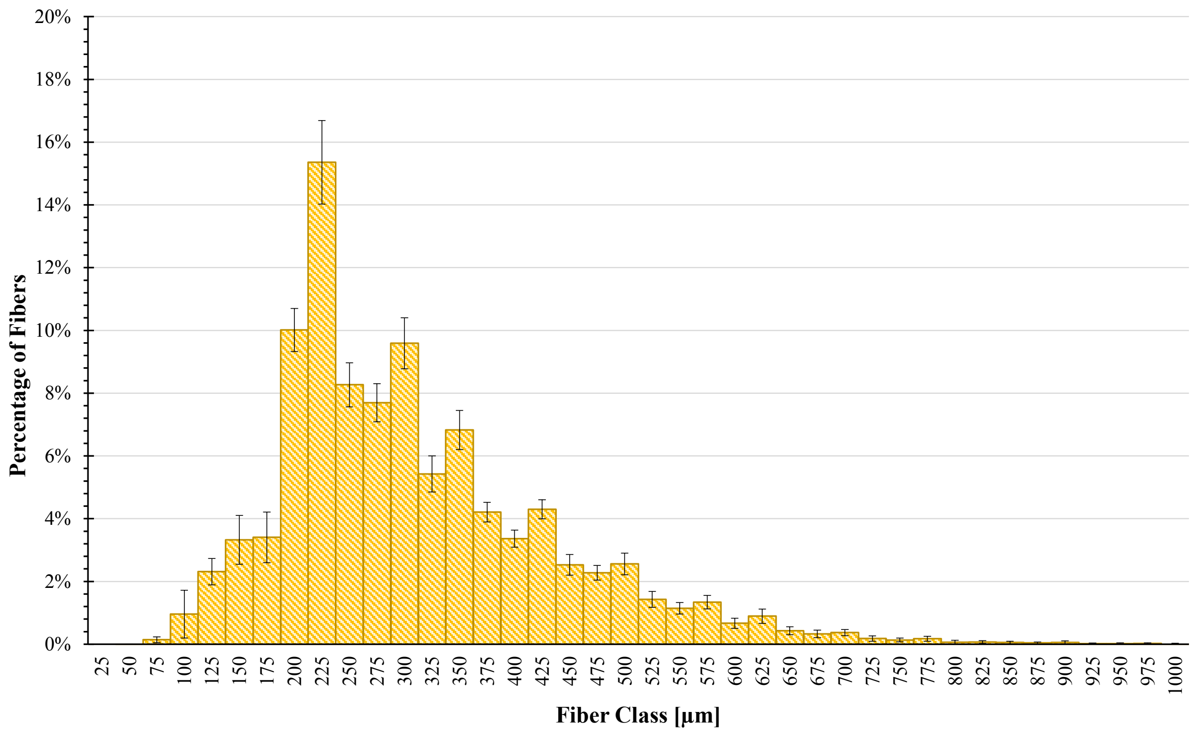


Figure 6: Fiber Length Distribution

The characteristic mechanical values obtained in these experiments are shown below in relation to the varied process parameters (Figure 7). The tensile strength is used as a goal in the experiments; optimization of the injection molding parameters is carried out based on this value. Aside from the tensile strength, the values for the impact strength and the Young's modulus are also ascertained. The average values are shown for each operating point including the standard deviation.

A comparison of the results for varying melt temperatures in the two phases makes visible the influence on the mechanical properties. The influence on the tensile strength appears to be small; however, higher temperatures result in a significantly higher Young's modulus. The impact strength increases slightly as the temperature increases. These results show the positive influence which raising the temperature has on the specimen's mechanical properties.

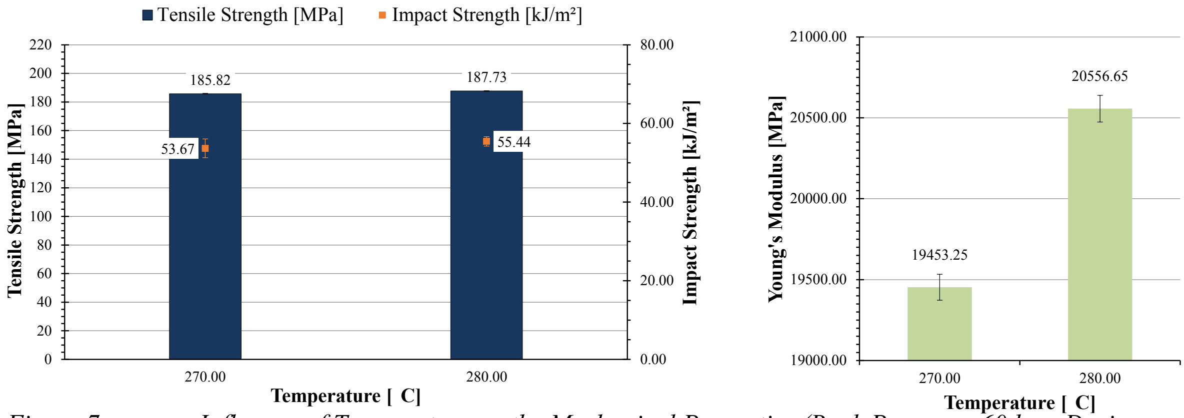


Figure 7: Influence of Temperature on the Mechanical Properties (Back Pressure: 60 bar, Dosing Speed: 30 1/min)

An investigation of the effect of dosing speed is carried out at an increased temperature of 280° C (Figure 8). The dosing speed is varied to three different levels. It can be clearly seen that its influence on both the tensile strength and the impact strength of the specimens is minimal. A more or less optimal point is reached at 30 1/min; the Young's modulus obtained here exhibits a very high degree of reproducibility, as shown by the small standard deviation.

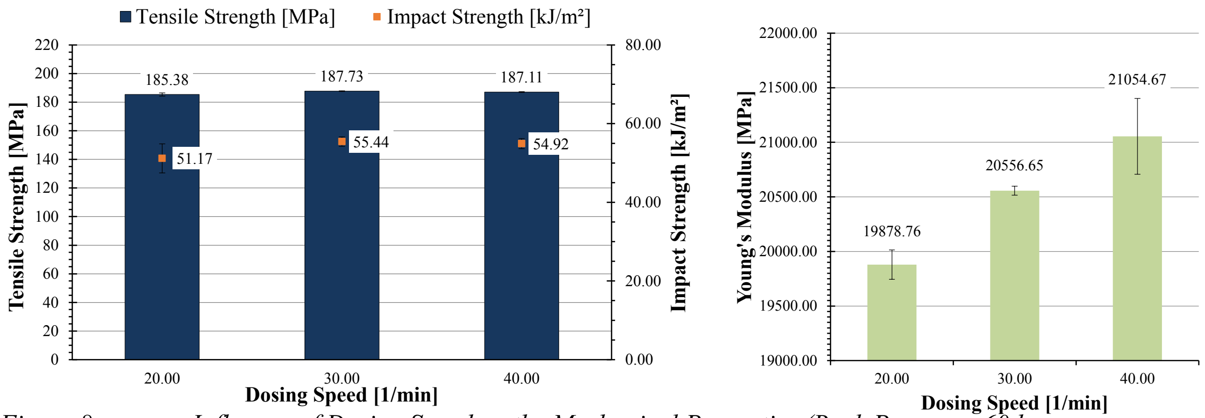


Figure 8: *Influence of Dosing Speed on the Mechanical Properties (Back Pressure: 60 bar, Temperature: 280°C)*

As well as the effect of the dosing speed, the influence of the back pressure on the mechanical properties is also examined (Figure 9). The optimized parameters from the previous experiments are used here in conjunction with an operating temperature of 280° C and a dosing speed of 30 1/min. No clear influence due to back pressure could be established, due to the only minor differences in tensile strength during the trials. The impact strength also does not appear to be significantly influenced by the back pressure. A significant effect on the Young's modulus can be clearly seen; however, this factor also shows very high standard deviations.

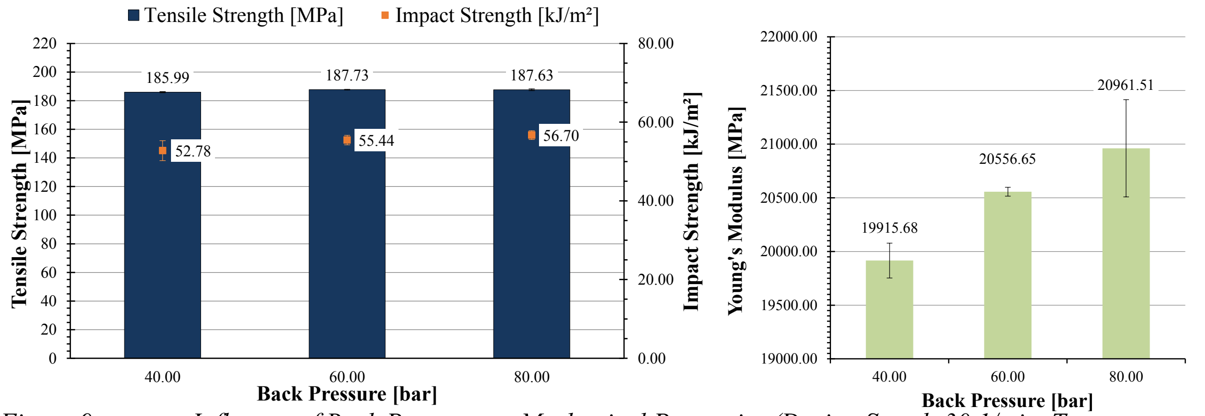


Figure 9: *Influence of Back Pressure on Mechanical Properties (Dosing Speed: 30 1/min, Temperature: 280°C)*

The experimental results show that the dosing parameters have no significant influence on the tensile strength, the impact strength, or on the Young's modulus. The tensile strengths from various trials are all within a similar range around 187 MPa; this means that the tensile strength is also below that of comparable standard materials, such as Durethan BKV60 from Lanxess. According to the technical data sheet, this reinforced polyamide with 60% fibers has a tensile strength of 230 MPa when fresh out of the mold. Nor can the material examined here match the impact strength of Durethan BKV60 at 90 kJ/m^2.

With regard to stiffness, however, the granule remains competitive. The Young's modulus obtained in these experiments is notably higher than that of the BKV60 as given in the data sheets.

The lower tensile strength and impact strength seen here could be a result of the fiber length in the specimens; they could also, however, be caused by material damage during processing. The average fiber length measured for the specimens is 282 µm, which is therefore slightly shorter than the fiber length in the granule.

6. OUTLOOK

Future experiments will be carried out with in which the granule will be produced using a shortened-barrel twin-screw extruder. As made clear in the experiments described above, the injection molding process causes a slight shortening of the fibers. For this reason, longer fibers in the granule could lead to longer fibers in the specimens and could thus contribute to the achievement of better mechanical properties. The minimal shear effect and the shorter residence time in a shorter barrel cylinder would minimize fiber shortening and would thus increase the resulting fiber length in the granule [4]. This would also result in less damage to the matrix material.

7. ACKNOWLEDGEMENTS

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8. FIGURES, CHARTS AND GRAPHS

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